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SOMMARIO

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Problèmes actuels d'astrophysique.

Monsieur le Président, Mesdames, Messieurs,

Il serait très ambitieux de ma part de traiter de tous les problèmes actuels de l'astrophysique, en une heure. Aussi, je voudrais d'abord situer ce que je crois être les problèmes fondamentaux de l'astrophysique actuelle et montrer comment des travaux de caractère technique contribuent à la compréhension de ces problèmes et à leur solution. Un exemple permettra de montrer comment les solutions ont pu progresser au cours des dernières années.

Il n'y a pas de doute que l'un des problèmes essentiels est de savoir d'où nous venons et où nous allons; en d'autres termes, comment l'univers a évolué, quelle sera son évolution future; quelle a été dans cet univers l'origine des galaxies et l'origine des étoiles; comment evoluent les galaxies, les étoiles et comment au sein de la galaxie s'est formé le système solaire. Cette dernière question pourrait éventuellement nous amener aux problèmes de l'origine de la vie sur la Terre et de la pluralité des mondes habités.

Mais bien, que les astrophysiciens, sur ce dernier point, se soient livrés à quelques spéculations intéressantes ce n'ets cependant pas cette question-là que je voudrais aborder: C'est plutôt aux biologistes qu'il faudrait la laisser.

Examiner comment les efforts faits dans des domains très divers convergent vers la solution des problèmes enumerés plus haut est une question de methodologie et d'epistemologie qu'il n'est pas de mon propos d'aborder ici.

Le problème qui en astrophysique a peut-être coûte au cours des trente ou quarante dernières années les plus grands efforts a sans doute été l'étude quantitative des spectres stellaires.

Il a fallu réunir des observations de meilleure qualité que par le passé, élaborer des modèles d'atmosphères stellaires pour trouver comment varient dans une atmosphère stellaire la densité, la température, le degré d'excitation ou d'ionisation des différentes espèces chimiques, pour pouvoir calculer l'intensités des raies spectrales et pouvoir faire coincider du mieux possible les modèles théoriques avec les observations.

L'un des résultats les plus importants qui ont été obtenu, a été la détermination des abondances des espèces chimiques.

La première détermination que l'on ait faite dans ce domaine date d'il y a à peu près quarante ans, quand Russell a donné une estimation des abondances des éléments dans l'atmosphère solaire. Pendant très longtemps les seules sources d'information ont été l'abondance des éléments dans l'atmosphère solaire, l'abondance des éléments dans la croûte terrestre et l'abondance des éléments dans les météorites.

La tentation la plus grande était d'unifier ces différentes données pour en tirer une table de l'abondance cosmique des éléments. Mais cela etait imprudent. En faisant cette unification, on negligeait une très grande variété de processus par lesquels les éléments chimiques peuvent subir un triage physique. L'histoire du système solaire est complexe et en réalité il n'y a aucune raison de croire que l'abondance des éléments soit la même sur la Terre, dans les météorites et dans le Soleil dans son état actuel.

Mais ce qu'il y a d'intéressant dans l'étude dé l'abondance des éléments, c'est que les noyaux atomiques subissent des transformations dans des conditions très particulières et dans le fond relativement exceptionnelles.

En effet dans les conditions physiques et chimiques ordinaires, puisque les nouyaux sont extrêmement stables ou se conservent on peut les considérer comme des fossiles, témoins

d'événements beaucoup plus importants qui les ont affectés. Autrement dit, on peut considérer les noyaux atomiques comme des traceurs d'évènements astrophysiques du passé. Par conséquent lorsqu'il est apparu que la determination des abondances des éléments pouvait donner la clé de certains événements de l'histoire de la galaxie ou de l'histoire des étoiles, on s'est attaché à une détermination precise des abondances à la surface du Soleil et à la surface des étoiles.

On peut considérer les problèmes des abondances des éléments de deux points de vue. On peut le considérer du point de vue de la stabilité des espèces nucléaires et on peut le considérer aussi du point de vue du domaine d'énergie dans lequel il faut se placer pour réussir à modifier les abondances des espèces chimiques.

Si l'on suit dans le plan (numéro atomique, poids atomique) la surface d'énergie de liaison des noyaux on trouve suivant le domaine de cette surface où l'on se trouve une correspondance avec des conditions physiques differentes de destruction ou de formation.

C'est dans ces conditions que l'on peut essayer d'embrasser l'ensemble du problème de l'abondance et essayer de remonter dans le passé pour trouver comment les elements ont été produits.

Je voudrais prendre ce problème comme exemple, ce qui me donnera l'occasion d'aborder toute une serie de problème d'actualité de l'astrophysique et me permettra aussi de montrer le lien étroit entre des branches extrêmement diverses de la physique.

Commençons par le problème de l'hélium. Lorsqu'elles sont sur la séquence principale, les étoiles tirent leur énergie de la fusion de l'hydrogène et de sa transformation en hélium. Si l'on attribue la totalité de la luminosité d'une galaxie à la transformation d'hydrogène en hélium, on peut aisément calculer le taux de transformation actuel de l'hydrogène en hélium. Dans l'hypothèse d'un univers ayant dix milliards

d'années d'âge, on peut donc évaluer la quantité d'hélium ainsi produite.

Le résultat inattendu est le suivant. L'abondance en masse de l'hélium formé dans ces conditions est de l'ordre d'un pourcent de la masse d'hydrogène, c'est-à-dire dans le fond une faible fraction de l'abondance de l'hydrogène dans la galaxie, alors que l'abondance d'hélium est beaucoup plus grande, au moins 10 % en poids et peut-être plus.

On en deduit que l'hélium ne résulte pas de l'évolution des étoiles, mais a été formé antérieurement à la formation des étoiles et est donc un des constituant fondamentaux de l'univers, avec l'hydrogène. C'est un peu le problème que cherchait aborder Gamow il y a 23 ans lorsqu'il a fait son modèle de « big bang » et a essayé d'expliquer par la cascade des réactions nucléaires dans un univers chaud l'abondance des élements. Un problème essentiel est donc la determination exacte de l'abondance de l'hélium.

Les méthodes que l'on peut employer sont les suivantes:

1) On peut chercher à déterminer l'abondance de l'hélium dans les atmosphères stellaires, mais ceci à condition que les raies de l'hélium soient présentes, ce qui nous limite à un groupe d'étoiles très chaudes dans lesquelles les raies d'hélium neutre ou d'hélium ionisé peuvent se trouver excitées.

Ces étoiles sont toutes des étoiles jeunes, ce qui fait qu'elles peuvent tout au plus nous donner une information sur l'abondance de l'hélium dans des conditions récentes de formation des étoiles; à condition naturellement que d'autres processus ne soient pas intervenus et que l'abondance d'hélium à la surface de ces étoiles reflète vraiment l'abondance d'hélium dans les régions centrales.

Au moins en principe cette méthode directe est utilisable, mais elle ne nous informe pas sur la quantité d'hélium primitif présent dans la galaxie.

2) On peut mésurer l'intensité des raies de l'hélium dans les nébuleuses planétaires, mais, les nébuleuses planétaires

naissent à la suite d'un processus évolutif complexe et il n'y a pas de raison de penser que l'abondance de l'hélium dans les nébuleuses planétaires est caractéristique de l'abondance de l'hélium dans les conditions primitives.

3) Un autre procédé, plus délicat parce qu'il met en cause des intermédiaires théoriques beaucoup plus nombreux, est le suivant. On peut construire par le calcul des modèles de structure interne des étoiles afin d'expliquer quantitativement les propriétés photométriques des étoiles dans certains amas d'étoiles que l'on appelle les amas globulaires.

Notre galaxie, qui comprend environ cent milliards d'étoiles, est environnée par un cortège d'amas qui comportent suivant le cas de dix mille à quelques centaines de milliers d'étoiles. Ces amas sont des groupements sphéroidaux dans lesquels les étoiles sont réunies par la gravitation. Ce sont très certainement des objets dans lesquels toutes les étoiles ont été formées simultanément.

Les études théoriques sur l'évolution stellaire nous indiquent que ces objets sont très âgés, peut-être huit ou neuf milliards d'années (1).

Les modèles dependent de la composition chimique. Ils nous montrent que les étoiles d'amas globulaires sont presque certainement des étoiles pauvres en métaux et riches en hélium,

(1) Il y a une grande imprécision dans l'âge à cause de la difficulté de construire à l'heure actuelle des modèles complètement dignes de confiance.

En effet, pour construire ces modèles dans le détail il faut connaître pour une composition chimique donnée les grandeurs de transport, et particulièrement le coefficient d'absorption du rayonnement. Nul ne peut dire si les valeurs qu'on a actuellement sont suffisamment bonnes pour permettre des descriptions quantitatives exactes de l'évolution.

De plus, l'évolution résulte des réactions thérmonucléaires à l'intérieur de ces objets et il n'est pas sur que les sections efficaces sur lesquelles reposent la détermination des taux de production d'énergie soient connues de façon définitive.

l'abondance d'hélium attégnant peut être 30% en poids de la composition totale.

On a donc une idée de l'abondance de l'hélium dans les étoiles vieilles. Mais avant d'en tirer aucune conclusion, je voudrais faire une digression sur un problème de structure interne du Soleil, pour montrer à quel point il est difficile d'affirmer qu'on possède à un monment donné un modèle définitif.

La séquence des évènements nucléaires qui se produisent à l'intérieur du Soleil constituent trois chaines. Dans la première chaine, la formation du deutérium et de l'hélium trois est suivie d'une réaction entre noyaux d'hélium trois, donnant naissance à une particule alpha et deux protons. La deuxième et la troisième chaine commencent par la réaction hélium trois hélium quatre qui donne naissance au béryllium 7.

Dans la deuxième chaine, béryllium 7, instable, capture un électron pour donner du lithium 7 qui à son tour est détruit par un proton en donnant deux particules alpha.

Dans la troisième chaine le béryllium capture un proton pour donner du bore radio-actif qui decline un béryllium 8 qui se décompose à son tour en deux particules alpha.

Ces réactions s'accompagnent de la production de neutrinos. Les neutrinos, en raison de leur très faible section efficace, traversent le Soleil avec une probabilité de réaction d'environ 10^{-4}.

Pratiquement, tous les neutrinos produits dans les régions centrales du Soleil peuvent nous atteindre.

L'étude des neutrinos solaires peut donner, au moins en principe, une information sur l'intérieur du Soleil.

Des efforts ont été faits pour definir une expérience valable d'astronomie des neutrinos. Les neutrinos qui sont les plus commodes à détecter sont ceux qui proviennent de l'avant--dernière des réactions de la troisième chaine, eux que le Béryllium 8 decline en donnant un électron positif plus un neutrino.

Ces neutrinos ont une énergie de 1,6 millions d'électron-volt, et peuvent être capturés sur du chlore 37, qui donne de l'argon 37 radio-actif, qui à son tour peut être détecté.

Cette expérience a été tentée aux Etats-Unis, d'abord avec un récipient de 400 litres de trichloréthylène. Le resultat negatif de cette première expérience a seulement montré que la température centrale du Soleil était inférieure à 20 millions de dégrés.

On a calculé ensuite que pour réussir l'expérience, compte tenu de notre connaissance de la structure interne du Soleil, il fallait opérer sur 400 m3 de tetrachloréthylène pour que la production d'argon radio-actif dans le réservoir soit suffisante pour être detectée.

Je passe sur les précautions à prendre, comme par exemple faire l'expérience au fond d'une mine, ce qui protège des rayons cosmiques, mais n'empèche pas bien, entendu les neutrinos de traverser 1500 mètres de terre.

Le résultat de cette deuxième expérience a été egalement négatif. Etant donné le seuil de détection, on peut affirmer que le flux de neutrinos solaires est au maximum un tiers du flux l'on s'attendait à détecter.

On peut espérer résoudre la difficulté du defaut de neutrinos solaires de différentes façons:

a) On attribue une abondance solaire de l'hélium (He 4) inférieure à l'abondance habituellement choisie. Ceci réduit dans la même proportion le nombre de réactions. Il y a cependant des limites dans le choix de l'abondance de l'hélium, et on ne peut expliquer de cette façon la différence entre le nombre de neutrinos observés et espérés.

b) On attribue la différence a un phénomène de diffusion. Le béryllium 7, au lieu de rester dans les régions centrales du Soleil, diffuse dans les régions périphériques, et est perdu pour la réaction de formation du Bore 8.

c) En réalité, il y a bien diffusion, mais ce n'est pas le béryllium qui diffuse. Disons d'abord un mot sur les mécanismes de diffusion.

Il nous faut écarter les processus microscopiques. Ces processus sont extrêmement lents car le libre parcours des parti-

cules dans les régions centrales du Soleil. Il ne reste donc à considerer que la diffusion turbulente. Celle ci obéit à une équation de diffusion et le problème peut être traité de la même façon que la diffusion thermique.

Si l'on admet qu'il y a diffusion des elements, le problème essentiel est de comparer le temps caractéristique de la diffusion au temps caractéristique de production ou de destruction de chacun des éléments produits dans les chaînes de réaction.

Or la durée de vie du béryllium 7 est nettement plus courte que le temps caractéristique de trasport par diffusion turbulente.

Par contre, la durée de vie de l'hélium 3 est sensiblement plus grande que le temps caractéristique de transport par diffusion turbulente.

En conclusion, le phénomène dominant est le transport de l'hélium 3 par diffusion turbulente en dehors de la région où il a été produit. A l'extérieur de cette région l'hélium trois ne réagit plus. La sous-production des neutrinos solaires serait due à la sous-abondance de l'hélium trois dans les régions centrales par diffusion turbulente.

Mentionnons en passant que des modifications importantes doivent être apportées au modèle solaire, car la quantité d'énergie disponible par proton est, sensiblement plus petite dans le regime stationnaire thérmonucléaire puisque il y a moins d'hélium 3 pour subir la fusion.

De même, il faut remettre en cause en partie les modèles de structure interne, tout au moins ceux dans lesquels la diffusion est un phénomène important.

Pour bien montrer que cette hypothèse de la diffusion turbulente n'est pas une hypothèse ad hoc, je voudrais montrer que le coefficient de diffusion turbulente qui permet d'expliquer la sous-abondance des neutrinos solaires est du même ordre de grandeur que le coefficient de diffusion turbulente que l'on doit introduire pour expliquer la destruction du lithium dans le Soleil, et que le moteur de cette turbulence est transfert de moment cinétique des régions centrales vers la surface. Faisons

un saut de la physique nucléaire à la mécanique rationnelle, ce qui, en même temps, est bien representatif de l'astrophysique, où tout est mélangé et où l'on ne peut pas parler d'une question sans aborder immédiatement plusieurs domaines de la physique. Le Soleil perd constamment du moment cinétique par éjection de matière par des processus où l'éjection de matière est couplée aux champs magnétiques solaires. L'effet de cette perte de moment cinétique est de produire un ralentissement des régions superficielles du Soleil. Près de la surface du Soleil, se trouve une vaste zone convective qui présente une viscosité turbulente extrêmement élevée, et, pour cette raison, est animée d'une rotation pratiquement identique à la rotation solide. La perte de moment cinétique, se traduit immédiatement par le ralentissement de la zone convective, mais lorsque la zone convective se met à tourner plus lentement, il se produit un glissement des couches solaires les unes par rapport aux autres et par un mécanisme qui s'apparente au mécanisme des couches limites apparaît une turbulence très lente. En ordre de grandeur, cette turbulence correspond à des échelles linéaires d'environ 10.000 km. et des vitesses de l'ordre du micron par seconde. Cette turbulence est inhabituelle, mais s'obtient tout de même lorsque on applique à la rotation différentielle les expressions de Von Kármàn. Le rôle de cette diffusion turbulente est d'apporter du moment cinétique de l'intérieur vers l'extérieur du Soleil et ainsi de remplacer au fur et à mesure ce qui a été perdu par éjection de matière.

On peut chercher l'ordre de grandeur du coefficient de diffusion turbulente, pour que, depuis la formation du Soleil, celui ci ait perdu vingt fois son moment cinétique initial. Le coefficient de diffusion turbulente est de l'ordre de 10^3-10^4.

J'en viens maintenant au problème du lithium. Herbig a montré que l'abondance du lithium dans les étoiles paraissait décroître au cours du temps. L'échelle du temps avec lequel le lithium se trouve détruit est de l'ordre de cent millions d'années.

Si l'on compare l'abondance du lithium solaire à l'abondance du lithium dans les étoiles très jeunes, on trouve que le lithium solaire est deficient par facteur 400. La température à la base de la zone convective ne dépasse pas 2.000.000 de degrés. Or, à deux millions de degrés, la durée de vie du lithium, est largement supérieure à l'âge du Soleil. Il ne faut pas monter beaucoup plus haut en température pour trouver une durée de vie plus courte. Déjà à 2.400.000 degrés la durée de vie du lithium est comparable à l'âge du Soleil. Mais les efforts deployés pour calculer des modèles solaires n'ont pas permis d'obtenir de modèle où température à la base de la couche convective atteigne la valeur critique de 2.400.000 degrés. Il y avait donc une contradiction entre la théorie et l'observation, qui paraissait prouver que la destruction du lithium se fait progrèssivement dans les étoiles, et qu'une étoile vieille a moins de lithium qu'une étoile jeune.

Mais le phénomène de diffusion turbulente, dont je viens de parler à propos du moment cinétique, permet de résoudre le problème. En effet, le lithium peut être transporté jusqu'à la couche trois millions de degrés. Là, le lithium est brûlé presque instantanément. Il y a appauvrissement progressif des couches superficielles, puisque le lithium est constamment transporté par diffusion vers la région où il est détruit. Le temps caractéristique est alors le temps de transport du lithium depuis la base de la zone convective jusqu'à la zone trois millions de degrés. Connaissant le temps caractéristique et le facteur d'appauvrissement du lithium, on peut determiner le coefficient de diffusion. On trouve un coéfficient de l'ordre de 10^3-10^4. Enfin, en utilisant le même coéfficient, on trouve un appauvrissement du bon ordre de grandeur dans la production de neutrinos. En definitive, il paraît raisonnable de croire, que le phénomène de diffusion turbulente existe. Si l'on en tient compte qualitativement dans les modèles stellaires, on voit que l'âge des amas et les séquences évolutives sont modifiées.

Une modification importante des chemins évolutifs des étoiles vieilles rendraît caduque toutes les determinations de l'abondance de l'hélium par les méthodes de la structure interne, et l'on voit comment sont reliés des problèmes aussi divers que la détermination de l'abondance de l'hélium, l'abondance du lithium et la production des neutrinos solaires.

Je voudrais maintenant aborder un autre problème, également un problème d'abondance mais dans un cadre très différent: c'est le problème de l'abondance du deutérium terrestre.

L'abondance du deutérium est d'environ 1/5000^e de l'abondance de l'hydrogène. Chose curieuse, cette quantité de deutérium est extraordinairement élevée. Pour des raisons que le professeur Sciama nous exposera tout à l'heure, il est fort difficile de fabriquer le deutérium dans le « big bang ». Si on le fabrique, on ne fait pas assez de lithium, si on fait le lithium, on ne fait pas assez de deutérium.

L'on peut alors admettre que le deutérium terrestre a été entièrement produit dans les conditions existantes au moment de la formation du système solaire. On peut alors envisager l'abondance du deutérium, ainsi que l'abondance d'autres éléments comme un traceur des événements qui se sont produits au moment de la formation du système solaire.

Je crains, de ne pas avoir beaucoup de temps pour vous expliquer comment je vois le problème du deutérium dans le système solaire. L'idée essentielle à retenir est la suivante: On peut fabriquer du deutérium en cassant l'hélium. Il suffit de disposer pour cela de protons d'énergie supérieure à 20 millions d'électrons-volts. Mais, si on casse l'hélium de cette façon, on produit du deutérium, mais, pour des raisons énergétiques, en quantité insuffisante. La seule façon de produire le deutérium en quantité suffisante par rapport à l'hydrogène, consiste à imaginer qu'une séparation physique s'est produite et que l'hydrogène, au moins dans la région de la formation de la Terre, a quitté la nébuleuse primitive, plus rapidement que l'hélium. Si la perte d'hydrogène a été mille fois plus grande que la perte

d'hélium, on peut vérifier qu'il n'y a pas de difficulté à produire le deutérium terrestre. Il reste seulement à construire le modèle de la nébuleuse primitive dans laquelle ce mécanisme de separation peut avoir joué.

Il est assez réconfortant quand on procède à la description d'un modèle de nébuleuse primitive, de trouver un mécanisme d'evaporation de l'hydrogène, puisque dans la region des planètes telluriques il ne reste a pratiquement pas d'hydrogène.

Je voudrais pour terminer, dire un mot sur l'abondance d'éléments placés à l'autre bout du tableaux de Mendelejef: l'abondance des éléments radio-actifs.

L'abondance des éléments radio-actifs est dans le fond quelque chose de très mystérieux, puisque ceux-ci, déclinent au cours du temps. Leur abondance passée a dû nécessairement être beaucoup plus grande que l'abondance actuelle. En fait, il y a une limite supérieure à l'abondance de l'uranium. Les éléments radio-actifs ont été formés dans la galaxie postérieurement à la formation de la galaxie et peut-être pas très longtemps avant la formation du système solaire. Si on admet pour simplifier que l'uranium et le plomb radiogénique ont été produits au cours du même phénomène, on peut réussir à ce dater, ce phénomène, à condition de le décrire de façon à peu près raisonnable.

Ceci nous amène à rappeler rapidement quelle est la théorie actuelle de la formation des éléments dans les supernovae. Pour former les éléments radio-actifs il faut ajouter des neutrons à des éléments plus légers, à un rythme suffisamment rapide pour que le numéro atomique croisse avant qu'ils soient détruits par radioactivité. C'est ce que Burbidge, Fowler et Hoyle en 1957 ont appelé le processus rapide, le processus *r*.

Le processus *r*, semble-t-il, peut se declancher dans les supernovae à l'occasion de leur effondrement et de la production d'un nombre considérable de neutrons. Les couches extérieures, éjectées au cours de l'explosion, sont irradiées par une grande quantité de neutrons. L'élément le plus abondant,

le fer, capture assez de neutrons pour que se forment en un temps inférieur à une seconde, les éléments radio-actifs.

A partir de ce modèle, en supposant que les éléments radio-actifs ont été produits par la dernière supernova qui a explosé à proximité du système solaire, que ces elements se sont mélangés à la matière interstellaire et ont servi à constituer la bouillie originelle dans laquelle la Terre s'est formée, on trouve, que l'explosion a eu lieu un milliard et demi ou deux milliards d'années avant la formation du système solaire.

Mais dans le fond, quelle preuve avons-nous que c'est bien par ce processus que les éléments radio-actifs se forment? Sans doute connaissons quelques restes de supernovae particulièrement remarquables, comme la nébuleuse du crabe. Mais l'identification, il y a à peu près quatre mois maintenant, de l'une des étoiles du centre de la nébuleuse du Crabe à un *pulsar* est un argument observationnel en faveur de l'effondrement gravitationnel. L'étoile restante dans la nébuleuse du Crabe, trouvée d'abord par radio et ensuite identifiée optiquement, est presque certainement une étoile à neutrons, c'est-à-dire une étoile complètement effondrée.

La découverte des pulsars, l'une des plus remarquables de l'astronomie, apporte un élément essentiel au thème général d'étude des conditions dans lesquelles évoluent et se forment les étoiles.

Un tel exposé ne peut être que qualitatif. Cependant, j'espère avoir réussi à vous donner par quelques aperçus sur le problème de l'abondance des éléments, une idée de quelques-uns des problèmes actuels de l'astrophysique.

D. W. SCIAMA

The recent renaissance of observational cosmology.

It was just 51 years ago, in 1917, that Einstein inaugurated relativistic cosmology in the famous paper which introduced the finite but unbounded universe which is now named after him. Curiously enough this was a false start because the Einstein universe is static, self gravitation being overcome by the repulsive effect of the rather artificial cosmological term which Einstein added to his original field equations of 1915. No doubt it was natural to think in terms of a static universe in 1917, yet in that same year Einstein wrote another famous paper in which he discussed the thermodynamics of radiation in quantum theory, and introduced the A and B coefficients. Had he applied these considerations to his cosmological model he would have seen immediately that the existence of hot stars separated by cold stretches of interstellar space is not compatible with an infinitely old static system (Olbers' paradox). In the event de Sitter showed in the same year that the amended field equations admitted a nonstatic solution, and in 1922 the Russian meteorologist Friedmann discovered that the original field equations led to a range of possible expanding and contracting models. The contracting models can also be ruled out by thermodynamic considerations, leaving just models which, at least at the present time, must be expanding. Further work on these solutions was carried out by Weyl, Lemaitre, Eddington, Robertson, Tolman, Milne, McCrea and Walker, and by the mid thirties these homogeneous and isotropic models were well understood.

Parallel with this development came the observational discovery of the extragalactic nature of the spiral nebulae and the large red shifts in their spectra (large by comparison with stellar red shifts). Again the origins of this great discovery were somewhat confused. The first spiral nebula (hereafter called galaxy) to have its radial velocity measured was the Andromeda galaxy. This was in 1912, when Slipher of the Lowell Observatory found its spectrum to be *blue* shifted by about 200 kms^{-1}. By 1914 Slipher had measured the spectra of 14 galaxies all but two of which he found to be receding at a velocity of from 150 to 300 kms^{-1}. However, it was not until 1924 that it was shown conclusively (by Hubble) that the spiral galaxies lie outside our own Milky Way. Moreover, it was discovered only in 1926-27 (by Lindblad and Oort) that the Milky Way is in rotation, the velocity of the sun around the centre according to present estimates being about 250 kms^{-1}. This motion of the sun must clearly be corrected for, if we are to obtain the velocities of the galaxies relative to the Milky Way as a whole. It was in 1929 that Hubble first announced his linear relation between recession velocity and distance

$$v = \frac{r}{\tau}, \tag{1}$$

and we now know that his value for the Hubble constant τ was too small by a factor of about 5 (the present value is close to 10^{10} years with an unknown uncertainty which could be as large as 50%). In the next few years Humason and Hubble extended the observations out to velocities of about one seventh of the velocity of light and Hubble summarized the situation in his classic book *The Realm of the Nebulae*, published in 1936.

Thus by the mid thirties theory and observation were in satisfactory agreement in the sense that all the homogeneous isotropic world models led to the Hubble law, equation (1), in first approximation. The models differed in the next approximation, but not even the 200 inch telescope, which came

into operation in 1949, led to a reliable determination of the second order term. We do not know, for instance, whether the expansion of the universe will continue indefinitely or will be halted by self gravitation and turned into contraction. It seems fair to say that observational cosmology made very little progress from 1936 until the early sixties, when radioastronomy came to the rescue. On the theoretical side various unorthodox proposals were made, of which the most influential was the steady state theory of Bondi, Gold and Hoyle (1948) with its daring suggestion of the continual creation of matter. The evidence against this theory is now very strong, but in its time it played an important role in forcing Hoyle and his associates (E. M. and G. R. Burbidge and W. A. Fowler) to devise their theory of the origin of the elements in hot stars. As we shall see, this latter theory may still be largely correct (with the important exception of the origin of helium).

The sterility of observational cosmology ended dramatically in the early and mid sixties. In 1965 two separate and independent discoveries were made which rank with the greatest in astronomy and, from the cosmological point of view are nearly as significant as the discovery of the expansion of the universe itself. These are the detection of objects with extremely large red shifts and the discovery of the cosmic black body radiation. Needless to say we do not yet know the full implications of these discoveries, but already it is clear that we are experiencing a great renaissance of observational cosmology. For this reason I propose to devote the rest of this article to these developments, to help celebrate the Jubilee of The Institute of Physics and in recognition of the crucial role played by British physicists and radioastronomers.

The radio source counts.

The first attempt to use counts of radio sources to draw cosmological conclusions was made by Ryle and Scheuer in 1955. They had reason to believe that most of the radio sources

which were contained in the second Cambridge catalogue (2C) were extragalactic, so that the distribution of the sources had to do with the structure of the universe as a whole. Ryle and Scheuer came to the conclusion that the counts were incompatible with the steady state theory, and thereby provoked a long, and sometimes violent, controversy, echoes of which can still be heard occasionally today.

The counts themselves consist of the number $N(S)$ of radio sources per unit solid angle whose measured flux density at the operating frequency of the radio telescope exceeds the quantity S. Because of the inverse square law the relation between N and S which would be expected for a uniform distribution of stationary sources has the form

$$N \propto S^{-\frac{3}{2}} .$$

A plot of $\ln N$ against $\ln S$ would then be expected to be a straight line of slope $-3/2$. As we shall see, when the red shift of extragalactic objects is taken into account the quantity $NS^{\frac{3}{2}}$, instead of being independent of S, should decrease with decreasing S. In other words, the $\ln N/\ln S$ curve should be *flatter* than in the static case. The observed curve is, however, *steeper*.

The anomalous steepness found by Ryle and Scheuer was very marked indeed. For the fainter sources in their analysis the slope of the $\ln N/\ln S$ curve was -3. We now know that the 2C survey was confusion limited below a relatively large flux density S and that many of the faint sources recorded are actually spurious. Some part of the anomalous steepness is now believed to be due to this effect. Three years later, in 1958, Mills, Slee and Hill used their Sydney catalogue of sources to derive a new slope for the $\ln N/\ln S$ curve and obtained the value $-1{\cdot}8$ (although they regarded their results as compatible with a slope of $-1{\cdot}5$). This slope is still anomalously

steep, but it has been confirmed by many further surveys, such as those of Scott and Ryle, and of Gower. The most recent and comprehensive $\ln N/\ln S$ curve, based mainly on

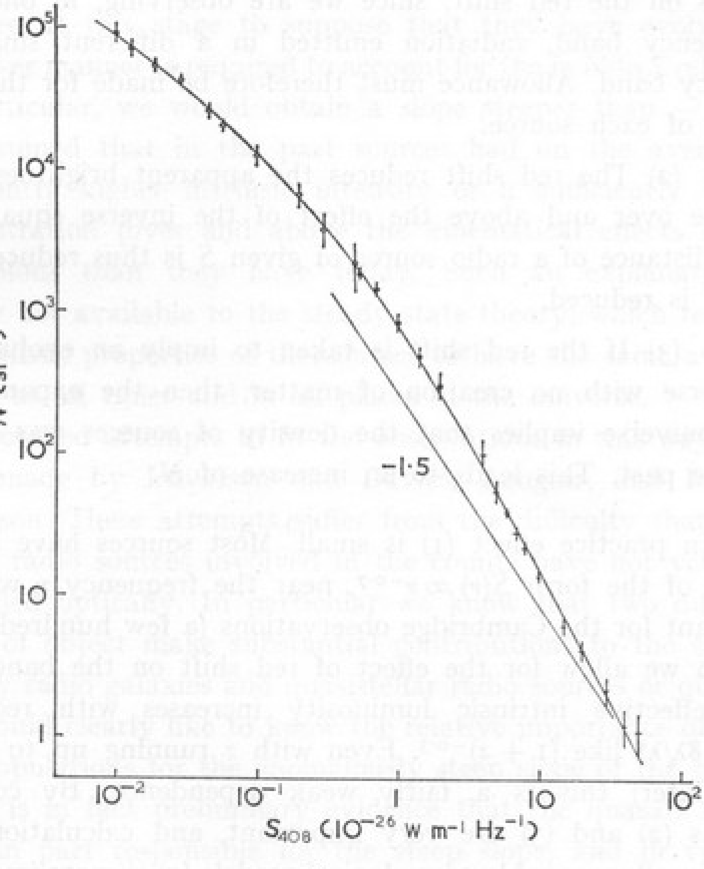

Fig. 1.

Counts of radio sources derived by Pooley and Ryle [1]. N is the number of sources per unit solid angle whose flux density at 408 MHz exceeds S_{408}.

Cambridge data, is that due to Ryle and Pooley (figure 1). It will be seen that for very low values of S the slope has flattened down to about -1.

We now consider the effects of the red shift on the simple theoretical three-halves power law. There are three such effects,

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[1] Published by courtesy of G. G. Pooley and M. Ryle.

all of which are of progressively increasing importance as S decreases:

(1) The effective intrinsic intensity of the sources depends on the red shift, since we are observing, in one small frequency band, radiation emitted in a different small frequency band. Allowance must therefore be made for the spectrum of each source.

(2) The red shift reduces the apparent brightness of a source over and above the effect of the inverse square law. The distance of a radio source of given S is thus reduced, and so N is reduced.

(3) If the red shift is taken to imply an evolutionary universe with no creation of matter, then the expansion of the universe implies that the density of sources was greater in the past. This leads to an increase of N.

In practice effect (1) is small. Most sources have a spectrum of the form $S(\nu) \propto \nu^{-0 \cdot 7}$, near the frequency ν which is relevant for the Cambridge observations (a few hundred MHz). When we allow for the effect of red shift on the bandwidth, the effective intrinsic luminosity increases with red shift z $(= \delta\lambda/\lambda)$ like $(1 + z)^{-0 \cdot 3}$. Even with z running up to 2 or 3 (see later) this is a fairly weak dependence. By contrast, effects (2) and (3) are very important, and calculation show that in all reasonable cosmological models (2) is more important than (3) (which is, of course, completely absent in the steady state model). Thus in all likely cosmological models the direct effect of the red shift is to *flatten* the slope of the $\ln N/\ln S$ relation. In this way we arrive at a complete contradiction with the observations.

This contradiction was resolved by Ryle and Scheuer by exploiting the fact that in an evolutionary universe objects with large red shift are being observed at an earlier stage in the development of the universe than are nearby objects of small red shift. The possibility then arises that there has been

a significant evolution in the intrinsic properties and distribution of radio sources in the time interval between emission and reception of the radiation. Since we lack a detailed understanding of the origin and development of these sources we are free at this stage to suppose that they have evolved in whatever manner is required to account for the $\ln N/\ln S$ relation. In particular, we would obtain a slope steeper than $-1{\cdot}5$ if we assumed that in the past sources had on the average a sufficiently higher intrinsic intensity or a sufficiently higher concentration (over and above the kinematical effects of the expansion) than they have today. Such an explanation is clearly not available to the steady state theory, which requires all intrinsic properties of the sources to have the same average values at all times and in all places in the universe.

Detailed attempts to fit the observations in this way have been made by Davidson and Davies, Longair, and Rowan-Robinson. These attempts suffer from the difficulty that most of the radio sources involved in the counts have not yet been identified optically. In particular we know that two different types of object make substantial contributions to the counts, namely radio galaxies and quasistellar radio sources or quasars. We would clearly like to know the relative importance of these two populations for the anomalously steep slope of the counts. There is in fact preliminary evidence that the quasars are at least in part responsible for the steep slope, and in view of their extraordinary nature, we shall discuss this evidence now, despite its tentative character.

Quasar counts.

The discovery of quasars is an oft-repeated story so we may be brief about it. It begins in 1960 when angular diameters were measured for the brightest 3C sources, thanks mainly to the work at Jodrell Bank. Several of these radio sources had very small angular diameters and so were of special interest. It later turned out that this was a somewhat accidental ap-

proach to the discovery of quasars, many of which have in fact substantial radio angular diameters. At any rate in 1960 it was of great interest that 3C48, 3C286, 3C196 and 3C147 had unusually small angular diameters. In September of that year Sandage took photographs with the 200 inch telescope of the regions containing the first three of these sources. These photographs were studied by Matthews who found that in each case the only visible object in the error rectangle of the radio position was what appeared to be a star. In October Sandage obtained a spectrum and photoelectric colours for 3C48. The optical spectrum was very strange, consisting of broad emission lines which could not be identified. Moreover the optical brightness varied appreciably on a time scale comparable with one day. The object was therefore regarded as a star with a puzzling spectrum.

All this was changed early in 1963 when the position of another 3C source, 3C273, was reported by Hazard, Mackey and Shimmins. This position had an unprecedented accuracy (better than 1 second of arc), being derived from observations of a lunar occultation of the source. There was therefore no doubt of its optical identification, which was of a thirteenth magnitude blue star. Schmidt obtained an optical spectrum of this object, which again had broad emission lines with no obvious identification. Then came the historic moment. Schmidt decided to see whether he could interpret the spectrum in terms of a substantial red shift despite the presumption that the objet was a star in our galaxy. He was successful. Four of the emission lines fitted very well with the H_α, H_β, H_γ, H_δ lines of hydrogen with a red shift $\delta\lambda/\lambda$ of 0·158 (a fifth hydrogen line in the red being discovered later by Oke), while the other emission lines also had immediate interpretations in terms of this red shift. If this is a Doppler shift the 'star' is moving away from us with nearly 16% of the speed of light. This result was published early in 1963, and the quasar era had begun.

It was immediately evident that if the red shift of 3C273 obeys the Hubble law, as the red shifts of radio galaxies appear

to do, then this source is exceedingly bright in intrinsic optical power. For its distance would be 5×10^8 parsec, and since it is of thirteenth magnitude its intrinsic optical brightness would be about 100 times greater than that of the brightest known galaxy. This raises profound problems for the astrophysicist, but for the cosmologist the significant inference is that quasars at much greater distances should still be readily detectable and yet have very large red shifts indeed. A first step towards the realization of this was achieved almost immediately. Stimulated by Schmidt's discovery Greenstein and Matthews solved the mystery of the spectrum of 3C48. This source is 3 magnitudes fainter than 3C273, and its spectrum becomes readily understood if it has a red shift of 0·367.

This is a very large red shift by Hubble's standards but it was soon far exceeded. In 1965 Schmidt found a quasar (3C9) with the fantastic red shift of 2·012, a source in which, for the first time, the basic hydrogen Lyman α line (1216 Å) was seen from the ground, shifted into the visible at 3666 Å. This great result required some intricate argumentation to justify, but so many large red shifts are now known that there is no longer any spectroscopic doubt about the interpretation. If we represent a red shift of 2 in terms of the Doppler formula of special relativity we find a velocity of recession close to 80% of the velocity of light. At last it seemed that Hubble's dream would be realized, that we could observe objects so distant that the linear approximation of equation (1) would be insufficient and that it would be possible to distinguish between the different cosmological models.

Unfortunately it has turned out that there is so much spread in the intrinsic properties of quasars, that they are far from being the 'standard candles' needed to make the cosmological test. Moreover, if these intrinsic properties vary with the cosmological epoch it will be extremely difficult to extract from the observations the correct model of the universe. The one test we can make is to see whether the steady state model is a possible one, since, as we have seen, this model permits

no epoch dependent effects. To make this test one takes the 40 or so quasars in the 3C catalogue whose red shifts are known, since these form a homogeneous sample. One then asks whether the number of quasars of different red shifts is in agreement with the steady state expectation. If I may venture a personal note at this point I would say that I was very much hoping that the steady state theory would survive this test. Alas it did not. My student Martin Rees pointed out to me that there were far too many quasars of large red shift. This result has since been found by several other investigators, the most thorough account having been recently published by Schmidt. It is, of course, significant that this discrepancy is in the sense to steepen the $\ln N/\ln S$ relation for quasars.

The only loophole would be to to deny that the red shift of quasars has a cosmological origin. It has been proposed by Terrell and by Hoyle and Burbidge that the quasars may be local, the red shift being either an ordinary Doppler effect unrelated to the expansion of the universe, or a gravitational effect. Along with most astronomers I find this very unlikely. The absence of blue shifts and the restrictions imposed by the known extragalactic radio background would require the quasar cluster nearest to our own local one to be very far away. It then becomes very improbable that we should be in a quasar cluster at all, not merely near the centre of one, as the observed isotropy would require. These are slim grounds on which to save the steady state theory. Moreover we shall meet another powerful argument against this theory when we come to discuss the cosmic black body radiation.

THE INTERGALACTIC MEDIUM.

Unless the process of galaxy formation is 100% efficient intergalactic space must contain residual gas. This gas has not yet been detected but it is potentially of great cosmological importance since it may make an appreciable contribution to

the mean density of matter in the universe. Indeed many of the relativistic cosmological models lead to a mean density far in excess of that due to the known galaxies. Of these the most attractive in many ways is the socalled Einstein-de Sitter model, in which the expansion continues indefinitely — but only just; that is, the velocity of expansion tends asymptotically to zero. In this model the present density ϱ is given by

$$\frac{8\pi}{3} G\varrho\tau^2 = 1 ,$$

where G is the Newtonian gravitational constant. With the Hubble constant $\tau \sim 10^{10}$ years we have

$$\varrho \sim 2 \times 10^{-29} \mathrm{gcm}^{-3} .$$

By contrast the mean density ϱ_g contributed by galaxies so far observed is unlikely to exceed 10^{-30}gcm^{-3}. Thus if the Einstein-de Sitter model is even approximately correct most of the matter in the universe is unaccounted for.

The form this missing matter might take has been much discussed. It could be made up of very faint galaxies or intergalactic stars, rocks or neutrinos, without having been detected. However, the most interesting possibility is that it is gaseous, since, as we shall see, it would then be on the verge of detection. We shall also see that its composition would probably be 90% hydrogen, and 10% helium (by number), with an admixture of heavy elements very much smaller than the relative abundance in our galaxy.

Intergalactic *atomic* hydrogen has been searched for by several radioastronomers who have attempted to detect the hyperfine transition at 21 cm both in emission and absorption. Their results have been negative, and despite some difficulties in interpretation one can say that the density of atomic hydrogen cannot significantly exceed the value 2×10^{-29}gcm^{-3}. A much more stringent limit has recently been obtained by considering the process of absorption at the Lyman α wave-

length. Normally this absorption would be undetectable below the atmosphere because it is in the far ultraviolet, but Scheuer, and Gunn and Peterson pointed out that the intergalactic gas near a quasar with a red shift of about 2 would absorb at a wavelength which for a terrestrial observer would be in the visible. Since the Lyman α absorption involves a resonance

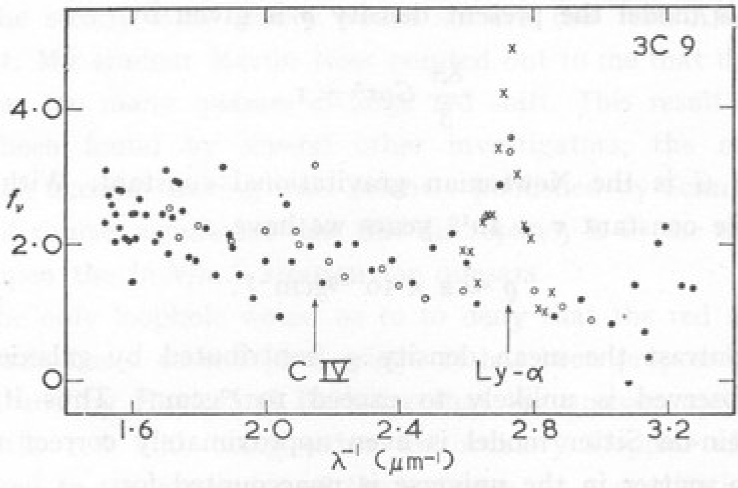

Fig. 2.

The photoelectric spectrum of the quasar 3C9, due to Oke and Wampler (²). Note that the level of the continuum does not change abruptly across the Lyman α emission line.

transition from the ground state this is a very sensitive method for detecting intergalactic atomic hydrogen. Careful inspection of the spectra of quasars with a red shift of about 2 has failed to reveal any absorption shortward of the Lyman α emission line in the quasars (for example *see* figure 2). The resulting limit on the present intergalactic density of atomic hydrogen is

$$\varrho_H < 10^{-36}\text{gcm}^{-3}.$$

By a similar analysis Field, Solomon and Wampler have placed an upper limit of 10^{-32} gcm^{-3} on the concentration of molecular hydrogen.

(²) Taken from WAMPLER, E. J., 1967, *Astrophys. J.*, *147*, 1, and reproduced by permission of the author and publisher.

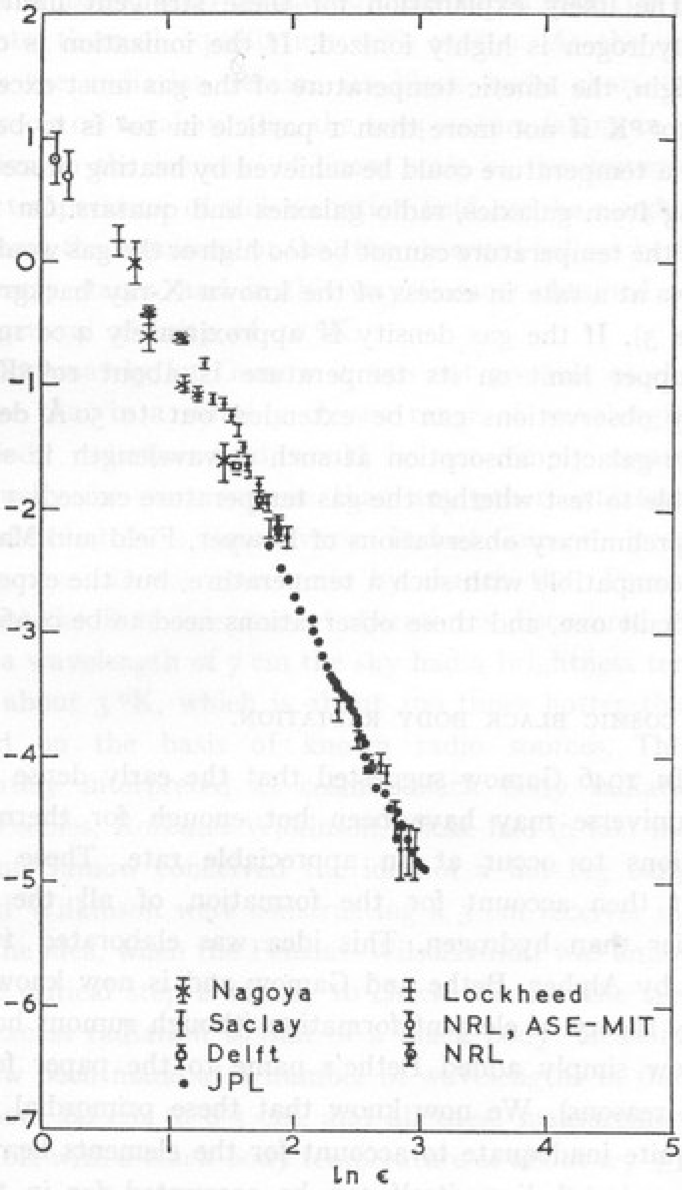

Fig. 3.

The diffuse x-ray background ([3]). ϵ is the x-ray energy (keV), and $j(\epsilon)$ the flux (photons cm^{-1} s^{-1} keV^{-1}).

([3]) Taken from GOULD, R. J., 1967, *Am. J. Phys.*, 25, 376, and reproduced by permission of the author and publisher.

The likely explanation for these stringent limits is that the hydrogen is highly ionized. If the ionization is collisional in origin, the kinetic temperature of the gas must exceed about 3×10^5 °K if not more than 1 particle in 10^7 is to be neutral. Such a temperature could be achieved by heating processes emanating from galaxies, radio galaxies and quasars. On the other hand the temperature cannot be too high or the gas would radiate X-rays at a rate in excess of the known X-ray background (*see* figure 3). If the gas density is approximately 2×10^{-29}gcm^{-3} the upper limit on its temperature is about 10^6 °K. If the X-ray observations can be extended out to 50 Å despite the severe galactic absorption at such a wavelength it should be possible to test whether the gas temperature exceeds 3×10^5 °K. The preliminary observations of Bowyer, Field and Mack are in fact compatible with such a temperature, but the experiment is a difficult one, and these observations need to be confirmed (4).

THE COSMIC BLACK BODY RADIATION.

In 1946 Gamow suggested that the early dense stages of the universe may have been hot enough for thermonuclear reactions to occur at an appreciable rate. These reactions might then account for the formation of all the elements heavier than hydrogen. This idea was elaborated two years later by Alpher, Bethe and Gamow and is now known as the α–β–γ theory of element formation (though rumour has it that Gamow simply added Bethe's name to the paper for alphabetic reasons). We now know that these primordial processes are quite inadequate to account for the elements heavier than helium, but helium itself can be accounted for in this way. Gamow showed that in the early stages there would be ample

(4) The observations have since been confirmed by Henry, Fritz, Meekins, Byram and Friedman, who claim to have actually observed a dense, hot, intergalactic gas. This interpretation of their observations is not the only possible one, however, and the question remains open.

time for a black body radiation field to be built up and to come into thermal equilibrium with matter. As the universe expands the radiation retains its black body character and simply cools off adiabatically, the temperature falling in inverse proportion to the increase of linear scale in the universe. The present temperature of this radiation field can be roughly estimated from the requirement that the observed helium be formed in the early stages, and in this way Gamow obtained a value in the general vicinity of 10 °K.

Unfortunately for Gamow it was not possible at the time to realize that in a suitably chosen range of wavelengths this black body radiation field would be not simply measurable, but actually far more intense than any other extraterrestrial source of radiation in the universe. In fact Gamow's prediction was forgotten. It was thus quite by chance that Penzias and Wilson of the Bell Telephone Laboratories discovered in 1965 that at a wavelength of 7 cm the sky had a brightness temperature of about 3 °K, which is about 100 times hotter than was expected on the basis of known radio sources. This was immediately interpreted as cosmic black body radiation by Dicke, Peebles, Roll and Wilkinson. Dicke had in fact independently of Gamow conceived the idea of a hot big bang, and Roll and Wilkinson were constructing a 3 cm receiver in order to test the idea, when the Penzias–Wilson result was announced.

The critical step is clearly to check whether the spectrum of the excess radiation is that of a black body. Measurements have now been made at a number of wavelengths in the range from about 60 cm to 0·3 cm, and all these measurements are compatible with a black body temperature of about $2{\cdot}7 \pm 0{\cdot}3$ °K (*see* figure 4). In addition there is an independent argument from the observed excitation of interstellar CN that the radiation field at 0·25 cm has a similar temperature, which again far exceeds that expected from known sources.

In view of the importance of this question it is necessary to examine these observations very critically. This is not, however, the appropriate place, and it suffices here to say that

the measurements, being absolute in character, are difficult to perform accurately and that relatively large corrections have to be made for extraneous effects such as atmospheric radiation, receiver noise etc. Despite these difficulties the general consensus of opinion seems to be that the measurements can be accepted as genuine, as we shall do for the remainder of this ar-

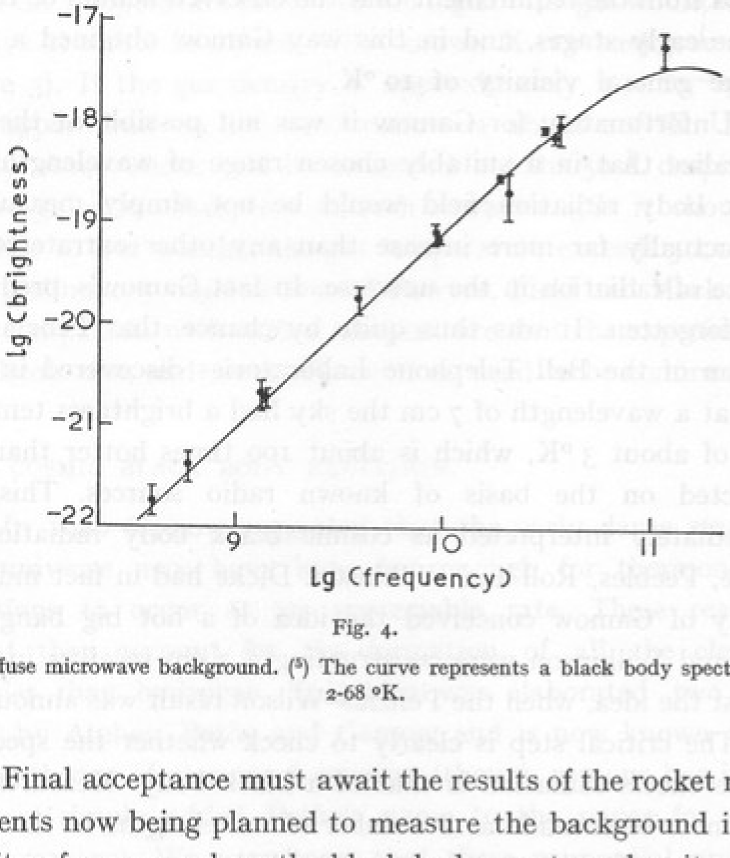

Fig. 4.

The diffuse microwave background. (5) The curve represents a black body spectrum at 2·68 °K.

ticle. Final acceptance must await the results of the rocket measurements now being planned to measure the background in the vicinity of 0·1 cm, where the black body spectrum has its peak.

We shall now discuss the following topics which relate to the existence of the cosmic black body radiation:

(1) The thermal history of the universe;
(2) The helium problem;

(5) After Shakeshaft, J. R., and Webster, A. S., 1968, *Nature*, *217*, 339; published by permission of the authors and *Nature*.

(3) Astrophysical effects of the black body radiation;

(4) The peculiar velocity of the earth;

(5) The isotropy of the universe;

(6) The homogeneity of the universe;

(7) Singularities in the universe.

The thermal history of the universe.

As we have mentioned, the temperature T of the black body radiation is related to the linear scale factor $R(t)$ of the universe as follows

$$T \propto R^{-1}(t) \,. \tag{2}$$

Accordingly the energy density of the radiation field ϱ_{rad} obeys the relation

$$\varrho_{\text{rad}} \propto R^{-4}(t) \,.$$

By contrast the density of matter ϱ_{mat} (if it is conserved) obeys the relation

$$\varrho_{\text{mat}} \propto R^{-3}(t) \,.$$

Now in the hot big bang models $R(t)$ was arbitrarily small in the past and so if there was any radiation at all, its energy density dominated that of matter at sufficiently early times. A radiation dominated universe is easy to handle in general relativity with the simple result:

$$R(t) \propto t^{\frac{1}{2}} \,(t \text{ small}) \,,$$

$$T_{\text{rad}} = \frac{10^{10}}{t^{\frac{1}{2}}} \,(t \text{ small}) \,. \tag{3}$$

At later times two important things happen. The radiation ceases to be strongly coupled to matter when the matter cools down sufficiently so that it can recombine into atomic hydrogen ($T \sim 3000\ {}^{\circ}\text{K}$) and the radiation ceases to dominate

energetically. If we assume that the matter behaves approximately as a perfect gas then when it is uncoupled from the radiation its temperature obeys the law

$$T_{\text{mat}} \propto R^{-2}(t) .$$

By comparison with equation (2) we see that the matter cools more rapidly than the radiation. Its temperature now should thus be much less than 3 °K, which contradicts the requirement of the last section that it should be about 3×10^5 °K. If this latter requirement is correct the intergalactic gas must have been reheated, presumably by emanations from galaxies, radio galaxies or quasars when they came into being.

It is useful to express the radiation/matter ratio in terms of the entropy per baryon S/n since this quantity is independent of time ($S_{\text{rad}} \propto T_{\text{rad}}{}^3 \propto R^{-3}(t)$). If the present value of the matter density is $2 \times 10^{-29}\text{gcm}^{-3}$ (Einstein–de Sitter universe) we obtain for the entropy of radiation per baryon the quantity $10^8 k$, where k is Boltzmann's constant. The hot big bang theory in its present form does not specify the processes which produced the observed heat. Either it is a question of the initial conditions at $t = 0$, or processes occurred later which we can legitimately speculate about. For the moment this is an unsolved problem, but we shall mention a possible explanation when we discuss (5), the isotropy of the universe.

The helium problem.

Investigation shows that wherever it can be measured spectroscopically or estimated theoretically (in the sun, the stars, the interstellar gas) helium has an abundance by number about 10% that of hydrogen. There are exceptions to this rule in the case of certain old stars, but there seems to be good evidence that these exceptions can be explained away. Now the stars in our galaxy could have manufactured only about 10% of the observed helium in the lifetime of the galaxy. It is therefore attractive to adopt the α–β–γ proposal that most

of the helium was formed by thermonuclear reactions in the early stages of the hot big bang.

We see from equation (3) that at a time of 1 s after the big bang the temperature throughout the universe was 10^{10} °K. This is beyond the threshold for the creation of electron–positron pairs. Neutrino pairs would also be thermally excited, and the weak and electromagnetic interactions would in fact be strong enough to ensure that thermal equilibrium would prevail between protons, neutrons, electron pairs, neutrino pairs and photons. When the temperature drops somewhat below 10^{10} °K the weak interactions can no longer maintain the neutrons in statistical balance with the protons because the concentration of electron pairs is beginning to drop abruptly. The neutron-proton ratio is then frozen in, until a few hundred seconds have passed and neutron decay begins to be appreciable. This frozen-in ratio, corresponding to thermal equilibrium at a temperature somewhat below 10^{10} °K, is about 15%.

The following nuclear reactions among others now take place:

$$\text{n} + \text{p} \rightarrow {}^2\text{H} + \gamma \tag{4}$$

$${}^2\text{H} + {}^2\text{H} \begin{cases} \nearrow {}^3\text{He} + \text{n} \\ \searrow {}^3\text{H} + \text{p} \end{cases}$$

$${}^3\text{He} + \text{n} \rightarrow {}^3\text{H} + \text{p}$$

$${}^3\text{H} + {}^2\text{H} \rightarrow {}^4\text{He} + \text{n}\,.$$

The first reaction, equation (4), is the slowest, and at temperatures exceeding 10^9 °K there are enough photons to disintegrate the deuterons as soon as they are formed. This is no longer true at 10^9 °K ($t = 100$s), so this is when the helium gets built up. At this stage the neutrons have their frozen-in abundance and nearly all of them combine with protons to form helium.

This frozen-in abundance depends only weakly on the material density and the entropy per baryon; the main depend-

ence is on the temperature and the properties of the weak interactions. Thus, so long as the material density is great enough for the key reaction (4) to be more rapid than the expansion time, this fixed concentration of neutrons is incorporated

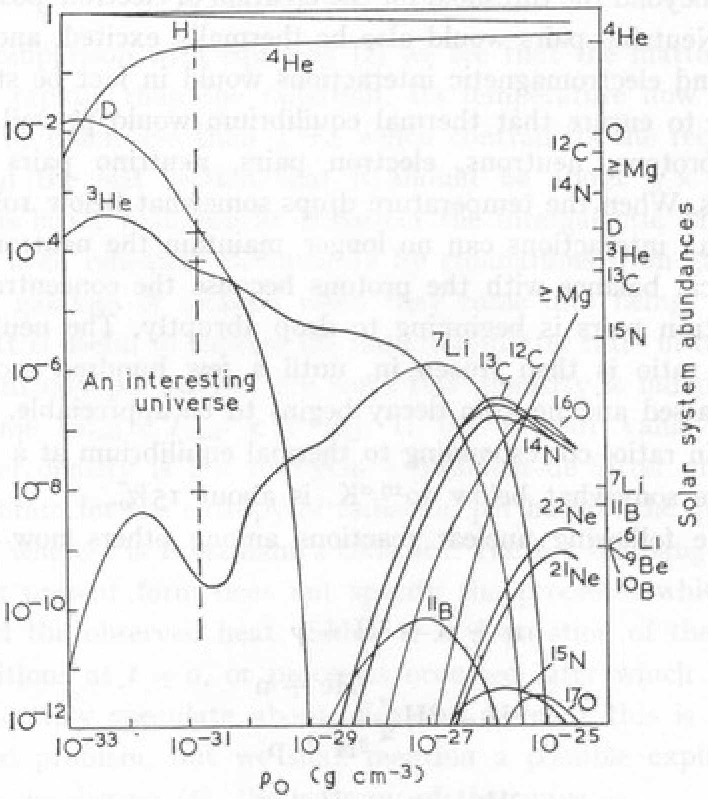

Fig. 5.

Element production in the hot big bang according to Wagoner, Fowler and Hoyle (6). The abscissa ρ_0 is the present mean density of matter in the universe.

into helium nuclei however great the material density may be. Thus the dependence of helium density on S/n has a plateau, which in fact is only appreciably departed from when S/n is so low that the universe was still matter dominated at 10^{10} °K.

(6) After WAGONER, R. V., FOWLER, W. A., and HOYLE, F., 1967, *Astrophys. J.*, *148*, 3; published by permission of the authors and publisher.

There have been many calculations of this plateau abundance. The most accurate were carried out by Peebles in 1966 and by Wagoner, Fowler and Hoyle in 1967, with results in good agreement with the observed relative abundance of 10 %. These results would be modified if the 10 % reduction that has recently been proposed in the half life of the neutron is correct. For the weak interaction coupling constant would have to be increased, and so the neutrons would remain longer in thermal equilibrium with the protons. This would mean that the frozen-in abundance of neutrons would be reduced and so the resulting abundance of helium would also be reduced. According to Tayler this reduction would be by 10 %, which is within the uncertainty of contemporary abundance determinations but is not altogether negligible.

The cosmological theory of the helium formation thus appears to be in good shape. However, the calculations of Wagoner, Fowler and Hoyle, which were very detailed (144 different reactions being included) show clearly that a negligible amount of elements heavier than helium is built up in these primordial reactions (*see* figure 5). The origin of these heavier elements thus has a different explanation; at the moment it is not clear whether the build-up occurs predominantly in supernovae or whether some form of massive exploding object must be invoked.

Astrophysical effects of the black body radiation.

From a laboratory viewpoint 3 °K is a low temperature. Indeed to measure it the microwave observers had to use a reference termination immersed in liquid helium. Nevertheless from an astrophysical viewpoint 3 °K is a high temperature. A universal black body radiation field at this temperature contributes an energy density everywhere of about 10^{-12} erg cm^{-3} or 1 ev cm^{-3}. This is just the energy density *in our galaxy* of the various modes of interstellar excitation — starlight, cosmic rays, magnetic fields and turbulent gas clouds. In intergalactic

space these energy densities probably drop off by a factor of between 100 and 1000, whereas the black body component maintains its energy density at 1 ev cm^{-3}. We may mention that the number density of these photons is about 10^3 cm^{-3} and the mean energy per photon is about 10^{-3} ev. These quantities are useful for making quick estimates of many of the effects of the radiation field, without having to consider in detail the full energy range of the photons in the Planck spectrum. We shall consider the effect of the radiation field on (*a*) cosmic ray electrons (*b*) cosmic ray protons and (*c*) cosmic ray photons.

Cosmic ray electrons: These electrons will transfer energy to the black body photons by means of the (inverse) Compton effect. A typical scattered photon would have an energy E' given by

$$E' \sim \gamma^2 E ,$$

where E is the original energy of the photon and γ is the relativistic factor of the electron $(1 - v^2/c^2)^{-\frac{1}{2}}$. Consider now the electrons which are responsible for the galactic radio background through their synchrotron emission (magnetic bremsstrahlung). A typical energy for such an electron might be, say, 1 Gev. Its γ would then be 2000, and with $E \sim 10^{-3}$ ev we see that the scattered photon would be raised in energy to about 4 kv. This takes us right into the X-ray region at a wavelength of 5 Å. The galaxy would thus be an extended X-ray source, and its radio properties imply that its X-ray intensity would be about 1 % of the observed X-ray background. This is not as low as it might seem because the rate of transfer of energy to the X-rays is proportional to the energy density in the radiation field and so to the fourth power of its temperature. Moreover the electron energy needed to produce a given X-ray wavelength is less for a radiation field whose photons have a greater mean energy, and there are more electrons of lower energy in the cosmic rays. The net resultof all this is that if the black body background had a temperature of say, 10 °K,

the X-ray flux from the galaxy would be greater, and the energy drain on the electrons would be very large indeed.

By the same token the X-rays emitted from great distances, at a time in the past when the black body temperature was greater than now, cannot be ignored. Indeed the currently most attractive explanation for the origin of the observed X-ray background is that it is mainly due to inverse Compton processes in distant radio sources, for not only is the radiation density much greater in the past but also, as we have seen in discussing the radio source counts, the concentration of intense radio sources was also much greater in the past. An alternative explanation is that the X-ray background arises from inverse Compton processes in intergalactic space. Whatever its explanation, the X-ray background is likely to be of great cosmological significance.

Cosmic ray protons: From the viewpoint of a cosmic ray proton of 10^{20} ev, which has a γ of 10^{11}, a photon of 10^{-3} ev looks like one of 100 mev. Such an energetic photon striking a stationary proton would be close to the threshold for producing a pion. This means that from the terrestrial viewpoint a cosmic ray proton of 10^{20} ev can collide with a black body photon, produce a pion, and so be degraded in energy. The importance of this process was first pointed out by Greisen who found that once the threshold is past the proton loses a substantial fraction of its energy in only 3×10^7 years. It is perhaps unlikely that cosmic rays with energies in the range 10^{18} to 10^{20} ev, which are almost certainly not confined to the Galaxy by its magnetic field, have a lifetime of less than about 10^{10} years. Greisen therefore proposed that the energy spectrum of cosmic rays would drop very steeply beyond 10^{20} ev. Now it so happens that the spectrum of cosmic rays been followed out to just about 10^{20} ev, without anything drastic being observed. This would imply that the black body temperature cannot significantly exceed 3 °K. Detectors are now being built to extend the spectrum into the range 10^{21} to 10^{22} ev. If our

present ideas are correct, not a single event should be detected. This has led some people to suggest that there is no need to build these detectors. In the present state of our knowledge this seems to me a very unscientific attitude.

Cosmic ray photons: If there are high energy cosmic γ-rays then above a threshold at $2{\cdot}5 \times 10^{14}$ ev they would be rapidly degraded in energy by interaction with black body photons leading to pair production. Such high energy γ-rays are now being searched for, but there are no definitive results as yet.

The peculiar velocity of the earth.

The original measurements of Penzias and Wilson showed that the black body background is isotropic to a precision of a few per cent. Later measurements by Partridge and Wilkinson (figure 6) and by Conklin and Bracewell (figure 7) increased the precision to a few tenths of a per cent. Now such an isotropic radiation field defines a rest frame, namely, that frame in which the radiation is observed to be isotropic. An observer moving relative to that frame would, by virtue of the Doppler effect, see an increased intensity in front of him and a decreased intensity behind him. Thus motion relative to the black body radiation, and so to the universe as a whole, can be directly measured. The lack of any observed anisotropy limits the peculiar velocity of the earth to about 300 km s^{-1}, and future measurements should improve this limit or, more likely, actually detect the peculiar velocity. The reason is that in addition to the motion of the earth around the sun at 30 km s^{-1}, the sun is moving around the centre of our galaxy at about 250 km s^{-1}, the galaxy as a whole is probably moving relative to the local group of galaxies at about 100 km s^{-1}, and the whole local group *may* be moving relative to the local supercluster of galaxies at a few hundred kilometres per second... It is clear then that a measurement of the net peculiar motion of the earth would be of great importance for our understanding of the hierarchy of irregularities in the universe. It would

also link up with Mach's principle, which asserts that local inertial frames are unaccelerated relative to the universe as a whole. We are here on the verge of great clarification.

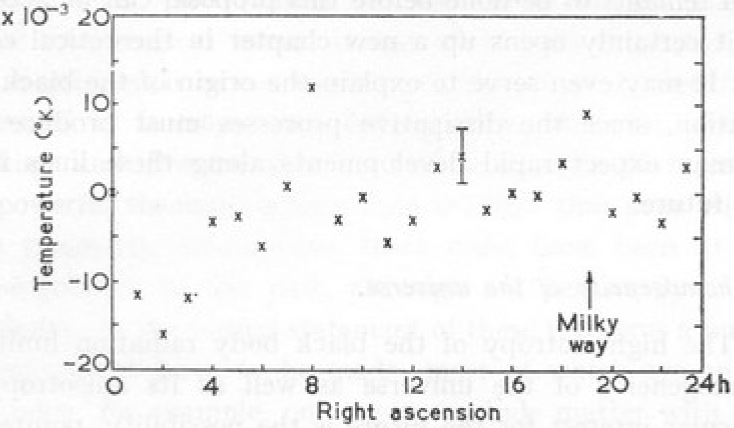

Fig. 6.

Changes in the temperature of the 3 cm background radiation along a circle parallel to the celestial equator at a declination of —8° (Wilkinson and Partridge) (7).

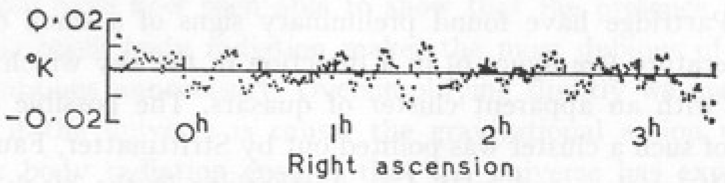

Fig. 7.

Same as fig. 6 for a different region of the sky (Conklin and Bracewell) (8).

The isotropy of the universe.

The fact that black body radiation is highly isotropic tells us that the expansion of the universe is highly isotropic too. Can we explain this or must we appeal to the initial conditions

(7) Taken from WILKINSON, D. T., and PARTRIDGE, R. B., 1967, *Nature, 215*, 719, and reproduced by permission of the authors and *Nature*.

(8) Taken from CONKLIN, E. K., and BRACEWELL, R. N., 1967, *Phys. Rev. Lett., 18*, 614, and reproduced by permission of the authors and publisher.

at $t = 0$? In an important new theoretical development, worked out most extensively by Misner, it has been proposed that any initial anisotropy may be dissipated away by viscous interactions. Much remains to be done before this proposal can be accepted, but it certainly opens up a new chapter in theoretical cosmology. It may even serve to explain the origin of the black body radiation, since the dissipative processes must produce heat. We may expect rapid developments along these lines in the near future.

The homogeneity of the universe.

The high isotropy of the black body radiation limits the inhomogeneity of the universe as well as its anisotropy. Of particular interest for the future is the possibility, pointed out by Sachs and Wolfe, that large scale density fluctuations could affect the black body temperature through the Einstein red shift. In this connection it is intriguing to note that Wilkinson and Partridge have found preliminary signs of a small dip in temperature (*see* figure 6) in a direction in the sky which coincides with an apparent cluster of quasars. The possible existence of such a cluster was pointed out by Strittmatter, Faulkner and Walmesley, and related to fluctuations in the black body temperature by Rees and myself. The evidence both for the temperature dip and the quasar cluster is quite uncertain at the moment, but in view of the importance of the problem we may expect the whole sky to be mapped out as precisely as possible in the next few years (9).

Singularities in the universe.

The final use to which we shall put the cosmic black body radiation is perhaps an unexpected one. We can use it to show that, according to general relativity, the universe must have

(9) Recent measurements at Princeton have shown that the evidence for the temperature drop is not significant.

been singular at some time or times in the past. It is well known that the exactly isotropic homogeneous (Friedmann or Robertson-Walker) models of the universe have a point singularity in the past (unless the field equations are modified by the cosmological term). It has often been suggested that this singularity is a consequence of the exact symmetry assumptions of isotropy and homogeneity. However, recently Hawking and Penrose have proved a number of important and powerful theorems which state in effect that even without these symmetry assumptions there must have been at least one singularity in the past, although not necessarily a point singularity. In the formal statement of these theorems a number of assumptions have to be made, most of which are entirely reasonable; for example, one has to exclude matter with negative energy density. However, some of these assumptions, while reasonable, are of a character that would be hard or impossible to check in the actual universe. Hawking, Ellis and Penrose have now been able to show that the presence of the cosmic black body radiation makes the most dubious of these assumptions unnecessary. Oversimplifying slightly we may say that if the universe is causal the gravitational action of the black body radiation ensures that the universe has expanded from one or more singularities, no physycally reasonable non-quantum equation of state being able to prevent it. Whether this result must be evaded, and if so how, is not known. We are here at the limits of existing theory.